Selection and implementation of aerosol data for the prediction of solar resource in United Arab Emirates

Armel Oumbe, Hélène Bru, Zhor Hassar, Philippe Blanc, Lucien Wald, Antoine Fournier, Dominique Goffe, Matteo Chiesa, Hosni Ghedira

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A. Oumbe[1*], H. Bru[1], Z. Hassar[1], P. Blanc[2], L. Wald[2], A. Fournier[3], D. Goffe[3], M. Chiesa[4], H. Ghedira[4]

* corresponding author: Armel Oumbe, Total SA, Immeuble Lafayette 3ème étage, 2 place des Vosges – La Défense 5, 92400 Courbevoie, France. E-mail: armel.oumbe-ndeffotsing@total.com

[1] Total New Energies, R&D – Concentrated Solar Technologies, France

[2] MINES ParisTech – Center for Energy and Processes, France

[3] Bertin Technologies – Energy Process Environment Department, France

[4] Masdar Institute of Sciences and Technologies, United Arab Emirates

Abstract

In deserts, as the sky is often dusty and rarely cloudy, aerosols are the most critical atmospheric parameter for solar resource estimation. High differences between existing aerosol datasets and low accuracies at solar irradiance estimates in Arabian Peninsula have been reported. This work is a part of a process aiming at developing a tool for irradiance estimation accounting correctly for aerosols. As hourly irradiances are the focus, only intra-day resolved aerosol data are of interest. The paper validates the MACC (re-analysis model) derived aerosol optical depth in United Arab Emirates, discusses its accuracy compared with that of MATCH (chemical transport model), evaluates the potential error on global and direct normal irradiances due to the observed error on aerosol optical depth, and then proposes an algorithm for implementation of MACC partial aersosol optical depths in the LibRadTran radiative transfer model.

Keywords: aerosol optical depth, direct normal irradiance, global horizontal irradiance, radiative transfer

1. Introduction

Understanding the spatial and temporal variability of available solar resource is necessary for appropriate site selection as well as for selection of the most appropriate solar energy conversion technology and design of a system for a specific location. Accurate resource data will remain essential to the efficient operation of a plant throughout its life span. The research program Predisol aims at developing a tool predicting downwelling irradiances in United Arab Emirates (UAE), in order to support present and future solar investments in this region. Interest in solar power is rapidly increasing in the Middle East. The UAE have set a target to cover 7% of its electricity demand from renewable energy sources by 2020. As part of this effort, a 100MW CSP plant, Shams-1, will be operational by the end of 2012, which is to be followed by Shams-2 and Shams-3 plants. That comes in addition to the 500MW PV rooftop project, which is to be completed within 20 years in the UAE.

The irradiance model in preparation is based on the radiative transfer model LibRadTran (www.libradtran.org). LibRadTran simulates the propagation of radiation through, the atmosphere with high accuracy and is widely used as a reference [1]. As the quality of LibRadTran estimations strongly depends on the quality of inputs, large efforts are made on the definition of such inputs. Of particular concern are the spectral aerosol optical depths as it is well known that the atmospheric extinction due to aerosols can typically reach up to 30% of the downwelling direct irradiance. In desert area, aerosols become even more critical for irradiance estimation. This work deals with the selection and implementation of a proper aerosol dataset in the Predisol model.

Within the framework of the European initiative for Global Monitoring for Environment and Security (GMES), the MACC (Monitoring Atmospheric Composition and Climate) project provides forecasts and analysis of atmospheric constituents such as aerosols and greenhouse and reactive gases among others. The quality of the MACC aerosol optical depths (AODs) re-analysis for UAE is investigated through comparisons with local AERONET (Aerosol Robotic Network) measurements and is benchmarked against AOD data from the MATCH (Model of Atmospheric Transport and Chemistry) chemical transport model. The deviation on irradiances that may be caused by these atmospheric factors is also evaluated. We then propose an algorithm to compute aerosol type from the partial aerosol optical depths provided by MACC re-analysis for 5 different species.

2. Aerosol data

2.1. AERONET AOD (Measurements)

AERONET provides ground-based sun photometer measurements of local AOD. The NASA-operated AERONET program gathers aerosol information and provides reference data for satellite retrievals of aerosol optical properties. Datasets are available at http://aeronet.gsfc.nasa.gov and contain AOD measurements at 16 different wavelengths - 1640, 1020, 870, 675, 667, 555, 551, 532, 531, 500, 490, 443, 440, 412, 380 and 340 nm - as well as solar zenith angles, total water vapor column measurements and several variability coefficients used for automatic cloud screening procedure. The cloud screening procedure often misinterprets high AOD values as clouds. Actually, AODs above 1 occur in dust outbreak events and are similar to clouds from the optical point of view. Some highly dusty cases are therefore filtered out. The accuracy of AERONET AOD values is ± 0.01 for wavelengths down to 440 nm and ± 0.02 for shorter wavelengths [2].

The parameter needed as input for clear-sky models is AOD at 550 nm ($AOD_{\lambda=550nm}$). It is therefore computed from AOD at 440 nm and AOD at 870 nm using the following equation:

$$AOD_{\lambda} = AOD_{\lambda 0} (\lambda / \lambda_0)^{-\alpha}$$

Where α is the Angstrom coefficient calculated from $AOD_{\lambda=440nm}$ and $AOD_{\lambda=870nm}$.

Since measurements at some AERONET stations correspond to a campaign and are performed on a short period, there are few stations available for MACC AOD validations. In 2004 the United Arab Emirates Aerosol Experiment took place providing a remarkably increased AERONET data availability in the Middle East. Therefore, the bulk of measurements in the Middle East corresponds to 2004 (see the measurement period of each station on Table 1). The following figure shows the stations in UAE. Measurements in Dalma, Al Qaa, Sir Bu Nuair, Maarco, Saih Salam, Umm Al Quwain, Smart, Smart Pol and Jabal Hafeet were made only in 2004. Only Mezaira station is currently operational.

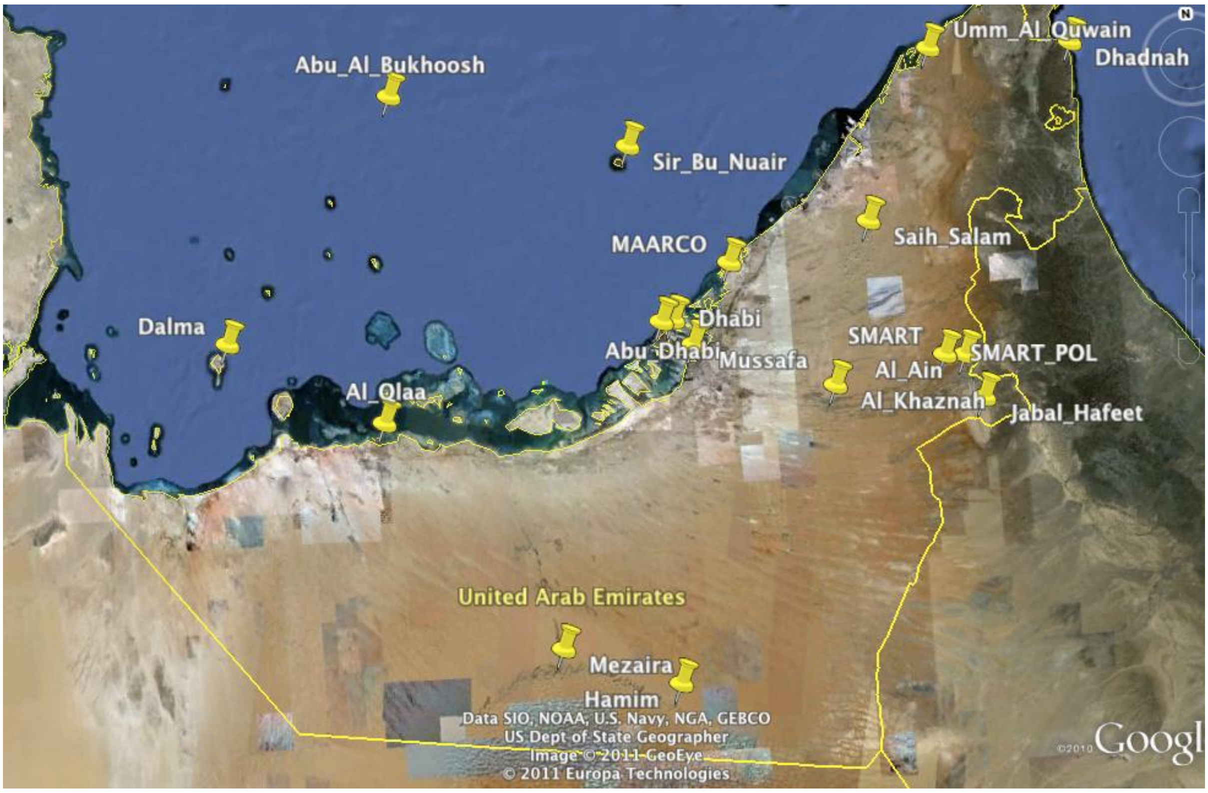

Fig. 1. AERONET stations in UAE.

2.2. AOD from MACC re-analysis model

Within the MACC project, European Centre for Medium-Range Weather Forecasts (ECMWF) predicts AOD on a global scale from re-analysis of meteorological satellite images and ground measurements. As part of the European initiative for Global Monitoring for Environment and Security (GMES), the Global and regional Earth-system Monitoring using Satellite and in situ data (GEMS) project has been funded to provide forecasts and analysis of atmospheric constituents such as aerosols, and greenhouse and reactive gases. The GEMS project integrates aerosols into numerical weather predictions and provides a monitoring and forecasting tool. Five types of tropospheric aerosols are considered: sea salt, dust, organic carbon, black carbon and sulphate aerosols. The two natural aerosols (sea salt and dust) have their sources linked to prognostic and diagnostic surface and near-surface model variables. In contrast, the anthropogenic aerosols (organic matter, black carbon and sulphate) have their sources read from external data sets. Several types of removal processes are considered: the dry deposition, including the turbulent transfer to the surface and the gravitational settling, and the wet deposition, including rainout and washout of aerosol particles in and below the clouds.

According to the ECMWF mission statement all Numerical Weather Prediction forecasts are provided in 3-hourly temporal resolution. MACC AOD predictions are obtained from the MARS archive on a global grid in reduced Gaussian Grid resolution (1.125° in latitude, 1° to 20° in longitude) from equator to pole. MACC data are now available only from 2003 to 2009. A detailed description on ECMWF/MACC aerosol forecasts may be found in [3] and [4].

2.3. AOD from the Chemical transport model MATCH

MATCH is a numerical aerosol model developed by NCAR (National Center for Atmospheric Research). It is a global offline model with a spatial resolution driven by meteorological input fields on a 1.9° Gaussian grid. The temporal resolution is set to 30 minutes and even 2 minutes in the sulphur chemistry sub-cycle.

The MATCH model provides the column AOD for several aerosol types as sulphates, organics, soot, dust, and sea salt. It includes emission databases for seasonal sulphur emissions at 0 and 100 m height for 1990 and 2005, monthly mean surface Dimethyl Sulfide emissions, monthly mean biomass burning black and organic carbon fluxes, monthly mean natural organic carbon fluxes from terpene emissions, fossil fuel black and organic carbon surface fluxes and an explicit dust mobilisation scheme. Physical and chemical processes include horizontal advection, convective and turbulent vertical transport, dry and wet deposition, cloud-aerosol interactions, the sulphur cycle, ageing, particle size transformation, and hygroscopic growth.

3. Comparison between the estimated AOD and measurements

All AERONET Level-2 measurements made in UAE are used as input data for the present analysis. The comparison between daily AODs extracted from the chemical transport model MATCH and AERONET measurements in the UAE shows generally a continuous positive bias. Strong overestimation with bias up to 0.23 and RMSE up to 0.37 is observed at Al Khaznah. Biases above 0.1 are obtained at Dhabi, Hamim, Jabal Hafeet, MAARCO, Mezaira, SMART and SMART_POL (7 out of 18 stations in this region). Also, the correlation coefficient is often less than 0.5. Generally, higher deviations are obtained for hourly comparisons. Detailed comparison and discussion about the source of deviation can be found in [5].

Overestimations are also observed between AERONET and MACC AODs, but more moderate. Generally, even the hourly deviations are lower than the daily deviations obtained with MATCH. The table 1 shows that the biases are above 0.1 at 3 stations (Dhabi, Hamin and Mezaira). The maximum bias is 0.12 (Mezaira) and the maximum RMS is 0.213 (Dhabi and Hamim). The correlation coefficient is generally good: it is less than 0.7 for only 2 stations out of 18.

Station	Mean	Bias	RMS	Correlation coefficient	Measurement period
Abu Al Bukhoosh	0.308	0.031	0.095	0.736	2004 - 2008
Al Ain	0.389	0.057	0.148	0.794	2006
Abu Dhabi	0.379	0.081	0.186	0.821	2004 - 2005
Al Khaznah	0.393	0.067	0.158	0.783	2004
Al Qlaa	0.346	0.069	0.159	0.593	2004
Dalma	0.363	0.062	0.148	0.683	2004
Dhabi	0.403	0.114	0.213	0.805	2003 - 2008
Dhadnah	0.395	0.054	0.147	0.796	2004 - 2010
Hamim	0.367	0.114	0.213	0.790	2004 - 2007
Jabal Hafeet	0.387	0.070	0.163	0.766	2004
MAARCO	0.384	0.089	0.186	0.818	2004
Mezaira	0.311	0.121	0.181	0.770	2004 - now
Mussafa	0.371	0.081	0.184	0.817	2004 - 2010
Saih Salam	0.406	0.085	0.185	0.810	2004
Sir Bu Nuair	0.381	0.048	0.164	0.590	2004
SMART	0.391	0.059	0.152	0.791	2004
SMART POL	0.389	0.059	0.151	0.791	2004
Umm Al Quwain	0.406	0.088	0.185	0.815	2004

Table 1. Hourly comparison between UAE AERONET and MACC AOD

The figure 2 depicts an overestimation of MACC AOD, but with high correlation coefficient. The color bar represents the number of points. RMS is the root mean square deviation and corr coef the correlation coefficient.

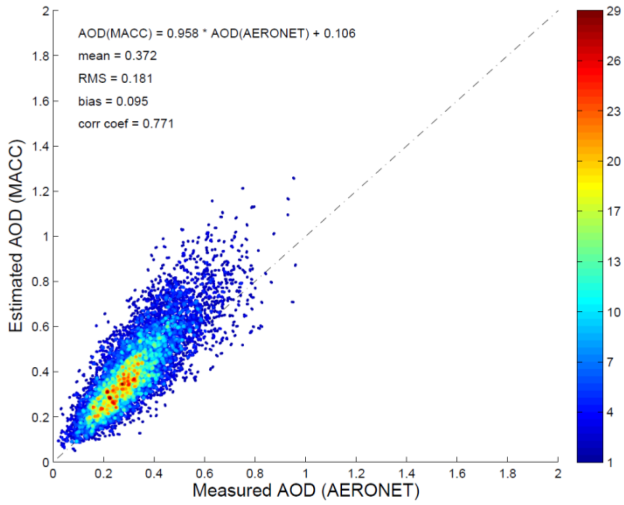

Fig. 2. Comparison between measured (AERONET) and estimated (MACC) hourly AOD at 550 nm, for all AERONET stations in UAE.

The overall comparison (figure 2) shows a 26% bias of AOD with MACC in UAE. The overall correlation coefficient remains high, but the relative RMS is also high: it reaches 49%. It might be necessary to make a post correction of the MACC AOD before using it on this region.

4. Influence of AOD on irradiance computation

All these AODs data are used as input to LibRadTran, and global horizontal irradiance (GHI) and direct normal irradiance (DNI) are estimated with AERONET AOD on one hand and with MACC AOD on the other hand for the corresponding period. All other atmospheric parameters are kept constant. Doing this, we evaluate the typical deviation that can be due to the quality of MACC AOD. The figure 3 exhibits a very low deviation on GHI: 5% RMS and very high correlation coefficient. High correlation coefficient is obtained for DNI as well (see figure 4) but the bias and RMS are not satisfactory: respectively 12% and 20%. The DNI, which corresponds to irradiance received only at the sun direction, and not hemispherical integrated as GHI, is more sensitive to the state of the atmosphere. A post-correction of the AOD error (figure 2) might be required before using MACC AOD in UAE for DNI computation.

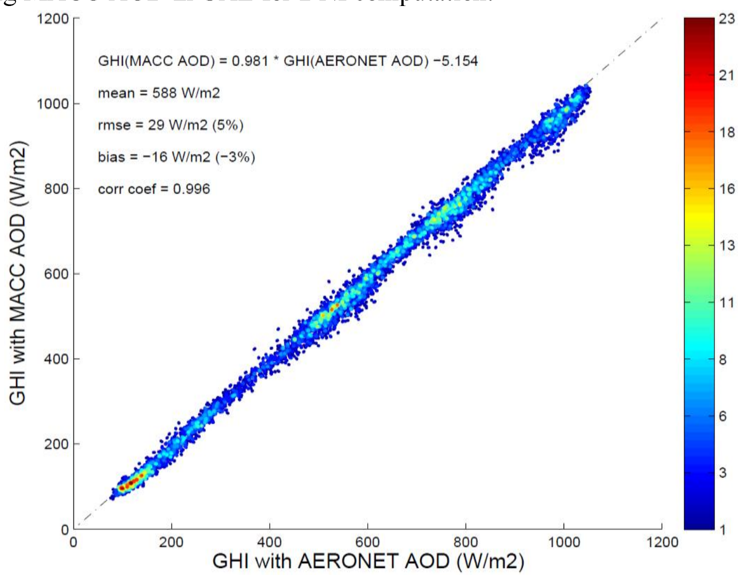

Fig. 3. Deviation on estimated GHI due to the MACC AOD, for all AERONET stations in UAE.

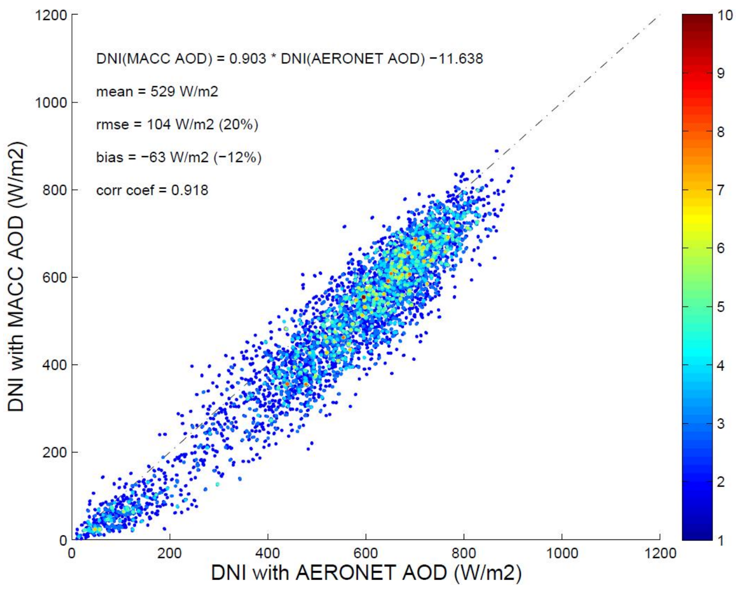

Fig. 4. Deviation on estimated DNI due to MACC AOD, for all AERONET stations in UAE.

5. Algorithm for aerosol type classification from the MACC partial AODs

The properties of aerosols – density of particles, size and height distributions, nature, origins – are highly variable both in time and space. These properties cannot currently be retrieved operationally from satellite images because of low aerosol reflectance and low frequency of observations. One needs to reduce the variability of naturally occurring aerosols to typical cases, but without neglecting extreme cases. The package OPAC (Optical Properties of Aerosols and Clouds – [6]) provides optical properties in the solar and terrestrial spectra for a range of mixture – or type – of aerosols sufficient to represent any kind of aerosol conditions. Since aerosol in a given location is a combination between locally-emitted and transported parts, there are not only desert aerosols in UAE but also maritime (as the region is closed to a sea) and anthropogenic (when closed to an urban or industrial area). So the aerosol type is not obviously known and has to be computed at each time step.

Generally, only partial and total AODs are provided. Every day at 0h, MACC predicts AODs at 0h, 3h, 6h, 9h, 12h, 15h, 18h and 21h (daily forecasting). Predicted quantities are total AOD at 550 nm, total AOD at 1240 nm, AOD of organic matter at 550 nm, AOD of black carbon at 550 nm, AOD of sea salt at 550 nm, AOD of dust at 550 nm and AOD of sulphate at 550 nm. The total AOD is the sum of individual AODs. The relative contribution of each aerosol species is easily determined.

In LibRadTran, 9 OPAC aerosol types are proposed to span the range of climatologically important aerosols: Urban, Continental Average, Continental Clean, Continental Polluted, Maritime Clean, Maritime Polluted, Maritime Tropical, Desert and Antarctic. The types are characterized by the relative and absolute amount of each aerosol component. The components are water-insoluble, water-soluble, soot (or black carbon), sea-salt, mineral, mineral transported and sulphate. **Continental average** aerosol is used to describe anthropogenically influenced continental areas. It is mainly made up of water-insoluble, water-soluble part and soot, with respective typical ratios of mass density 49%, 49% and 2%. **Continental clean** aerosol represents remote continental areas without or with very low anthropogenic influences – less than 0.5% of soot. It contains mainly water-insoluble (around 70%) and water soluble. **Continental polluted** aerosol is for areas highly polluted by man-made activities. The mass density of soot can reach 5%, and the mass density of water-soluble component is more than twice that in continental average aerosol. **Urban** aerosol represents strong pollution in urban areas. The mass density of soot is around 10%, and the mass densities of both water soluble and insoluble components are more than twice those of the continental average aerosol. **Desert** aerosol type is used to describe aerosol over deserts. It consists of the mineral aerosol components (around 90%), together with a small amount of the water-soluble and water-insoluble components. **Maritime clean** represents undisturbed remote maritime conditions with no soot, but with a certain amount of organic aerosol (around 20%). It is mainly made up of sea-salt, with a typical amount of 20 particles/m^3. **Maritime polluted** refers to a maritime environment under anthropogenic influence with highly variable amounts of soot and also of anthropogenic water-soluble particles. The sea salt components are kept unchanged compared to clean maritime. **Maritime tropical** aerosol, corresponding to tropical regions, has a low density of water-soluble substance. It is also assumed a lower wind speed (5 m/s) and a lower number density of sea salt. **Antarctic** aerosol can be found over the Antarctic continent, characterized by a high proportion of sulfate droplets (20%).

Referring to the analysis of the composition of OPAC aerosol type in libRadTran, we estimate the OPAC aerosol types from density of each aerosol species predicted by MACC. Threshold values of the algorithm are determined after several empirical trials of classification on locations where the type is known (eg. urban, maritime, desert areas) with MACC AODs. Typically, the aerosol OPAC type is set maritime if the sea salt is dominant, desert if dust is dominant, polluted if black carbon density is higher and tropical or Antarctic following the latitude. The chart flow is presented on figure 5. On the chart, the suffix *ss* means sea-salt, *du*: dust, *or*: organic matter (water-insoluble + water-soluble) and *bc*: black carbon.

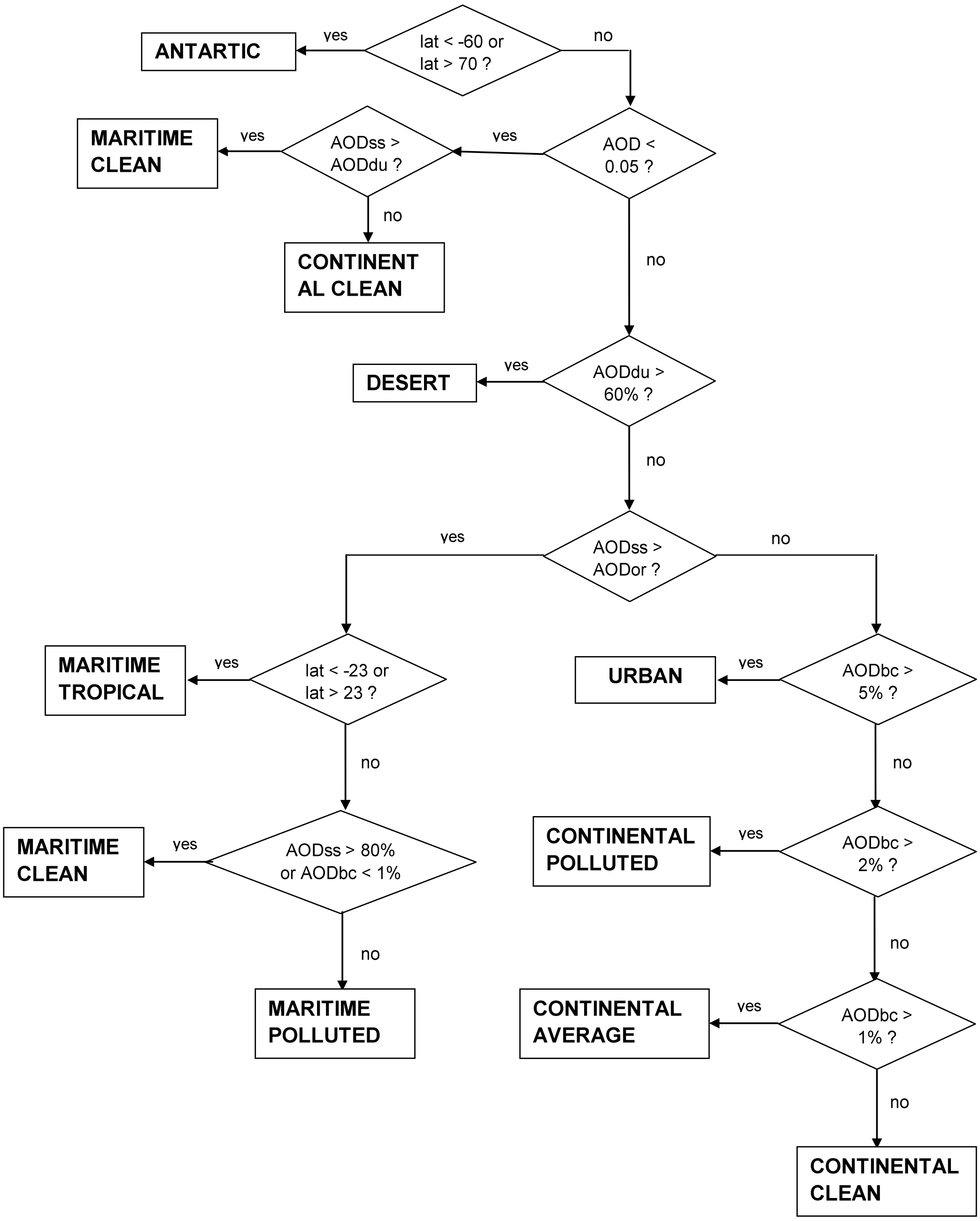

Fig. 5. Algorithm for classification of MACC partial AODs into OPAC aerosol types

The algorithm proposed is applied to MACC years 2003 – 2009 data for selected locations (figure 6). The aerosol type is computed each 3h.

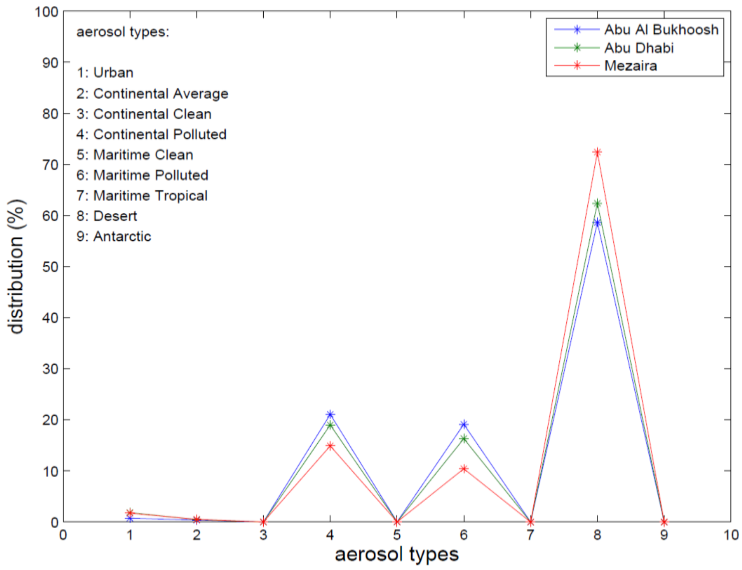

Fig. 6. Time Frequency Distribution of OPAC aerosol type at 3 AERONET stations

The classification confirms that there is a significant amount of anthropogenic aerosol in the region: the percentages of continental or maritime clean type are closed to zero. It also shows that the desert aerosol type is dominant in UAE: 60% or more. We also see that the locations are significantly influenced by maritime aerosol, as the UAE is close to the Arabian Gulf. The percentage of maritime aerosol is higher at Abu Al Bukhoosh which is on the sea, lower at Abu Dhabi on the coast, and minimal at Mezaira which is more country side.

The algorithm has been applied on locations were the aerosol type can be easily deduced: in the middle of ocean to verify if the aerosol types are mainly Maritimes, in the Antarctic to verify the Antarctic type, in highly pollution areas to verify if the urban and continental polluted is dominant, in pure rural areas, to verify if the aerosol type is mainly continental clean. These verifications did not reveal any major defect of the algorithm.

6. Conclusion

MACC AODs are up to now the most appropriate aerosol datasets for irradiance estimation in UAE. They are provided with a high frequency: 3-hourly resolution, they exhibit a relatively low deviation when compared to AERONET measurements, and will be long-term maintained, as part of an EU-funded project. The absolute error on MACC AOD (bias 0.095, RMS 0.181) may lead to low deviation on GHI computation by radiative transfer model (bias 3%, RMS 5%), but to high deviation on DNI (bias 12%, RMS 20%). This shows that these AODs need to be calibrated before use as input for irradiance calculation in our region of interest. Finally, the paper shows that aerosol types can be computed from the partial AODs with a good reliability.

Acknowledgements

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